

U.S. Adipic Acid and Nitric Acid N₂O Emissions 1990-2020: Inventories, Projections and Opportunities for Reductions

N₂O is a potent greenhouse gas (GHG). For this analysis the U.S. Environmental Protection Agency (EPA) assumes a global warming potential of 310 times the global warming potential (GWP) of carbon dioxide (CO₂) when normalized over 100 years and an atmospheric lifetime of 120 years (IPCC, 1996).¹ In 1999, the major sources of nitrous oxide (N₂O) in the U.S. were: agricultural soils (70.6%); mobile sources (14.7%); industrial sources (7.0%); manure management (4.1%); and stationary sources, including electricity, manufacturing and construction (3.7%). The focus of this paper includes two large industrial sources of N₂O emissions, which are adipic and nitric acid production. Other industrial sources include processes in which HNO₃ is used for oxidation purposes.

Prior to 1998, U.S. emissions of N₂O from adipic and nitric acid production averaged around 37 million metric tons of carbon dioxide equivalent (MMTCO₂E) per year. Industry efforts to reduce emissions since 1995 have resulted in lower future emissions from the production of Adipic Acid. In 2000, it is estimated that emissions from adipic and nitric acid production decreased to 29.7 MMTCO₂E per year. While substantial emission reductions have been made in this industry, further reductions can be made at low-cost.

This paper is organized in two major sections. The first section addresses the historical emissions of N₂O and presents EPA's forecast of emissions through 2020. This section also discusses the uncertainties around these estimates. The second section presents the options and costs of reducing N₂O emissions from the adipic and nitric acid industries. Data are presented on the cost of reducing emissions from these options and the amount of achievable emissions reductions.

1. Baseline Emissions from Adipic Acid and Nitric Acid Production

1.1 Sources of Adipic and Nitric Acid

Adipic acid. Adipic acid (C₆H₁₀O₄) is a white crystalline solid used primarily as the main constituent of nylon (nylon-6/6), representing about half of the nylon molecule. It is also used in the manufacture of some low-temperature synthetic lubricants, synthetic fibers, coatings, plastics, polyurethane resins, and plasticizers, and to give some imitation food products a tangy flavor.

Adipic acid is a dicarboxylic acid manufactured by a two-stage process. The first stage of manufacturing usually involves the oxidation of cyclohexane to form a cyclohexanone / cyclohexanol mixture. The second stage involves oxidizing this mixture with nitric acid to produce adipic acid. Nitrous oxide is generated as a by-product of the nitric acid oxidation stage and is emitted in the waste gas stream.

¹ Global Warming Potential (GWP) is used to convert emissions of Non-CO₂ greenhouse gases into equivalent emissions of CO₂. EPA uses the values for a 100-year time horizon in order to be consistent with other EPA greenhouse gas inventory reports. The values for the 100-year time horizon are from IPCC's Second Assessment Report and are the most commonly used GWP conversion factor.

Process emissions from the production of adipic acid vary depending upon the technologies and level of emissions controls employed by a facility. Adipic acid production also generates emissions of non-methane volatile organic compounds (NMVOC), carbon monoxide (CO), and nitrogen oxides (NO_x).

Worldwide, there are few adipic acid plants. The U.S. is the world's major producer, with three companies in four locations accounting for approximately 40 percent of world production. Adipic acid production is the largest *potential* source of industrial N₂O emissions. However, prior to 1990 two of the three major U.S. adipic acid producing plants implemented N₂O abatement technologies and as of 1998, the three major adipic acid production facilities had control systems in place. Only one small plant representing approximately 2 percent of production does not control for N₂O emissions (EPA, 2001).

Nitric acid. Nitric acid (HNO₃) is an inorganic compound used primarily to make synthetic commercial fertilizer. As a raw material, it is also used for the production of adipic acid and explosives, metal etching, and in the processing of ferrous metals. Now that adipic acid plants in the U.S. have implemented N₂O abatement technologies, nitric acid production is the largest industrial source of N₂O emissions.

Virtually all of the nitric acid produced in the United States is manufactured by the catalytic oxidation of ammonia (EPA, 1991). During this reaction, N₂O is formed as a by-product and is released from reactor vents to the atmosphere. While the waste gas stream may be cleansed of NO_x emissions, only a few plants currently use technology that eliminates both N₂O and NO_x emissions.

1.2 Methodology for Calculating Historical Emissions

Adipic Acid Historical Emissions. N₂O emissions are calculated by multiplying adipic acid production by the ratio of N₂O emitted per unit of adipic acid produced and then adjusting for the actual percentage of N₂O released as a result of plant-specific emission controls. On the basis of experiments (Thiemens and Trogler, 1991), the overall reaction stoichiometry for N₂O production in the preparation of adipic acid was estimated at approximately 0.3 kg of N₂O per kilogram of product. Emissions are determined using the following equation²:

$$\text{N}_2\text{O emissions (Adipic Acid)} = [\text{production of adipic acid}] \times [0.3 \text{ kg N}_2\text{O} / \text{kg adipic acid}] \\ \times [1 - (\text{N}_2\text{O destruction factor} \times \text{abatement system utility factor})]$$

The *N₂O destruction factor* represents the amount of N₂O, expressed as a percentage of N₂O emissions, destroyed by the currently installed abatement technology. The *abatement system utility factor* represents the percent of time that the abatement equipment operates. The net N₂O

² This equation and, hence, estimated N₂O emissions, is different than that used in the EPA (2000). An abatement system utility factor was determined to be a necessary part of the equation after further research conducted for the IPCC Expert Meeting on Industrial Gases, Washington, DC January 1999. All subsequent US GHG Inventories will be updated to reflect this change.

emissions are the product of the production level multiplied by the emissions factor, and reduced by the percent of emissions avoided due to the use of abatement technology.

Nitric Acid Historical Emissions. Nitrous oxide emissions are calculated by multiplying nitric acid production by the amount of N₂O emitted per unit of nitric acid produced. An emission factor of 9.5 kg N₂O / metric ton of HNO₃ used for N₂O production at uncontrolled plants. If NSCR is used for NO_x control, emissions are reduced by 80-90 % because the process of destroying NO_x also destroys N₂O. The emissions factor of 8 kg N₂O / metric ton HNO₃ is a combined factor comprising of 2 kg for plants using non-selective catalytic reduction (NSCR) systems and 9.5 kg for plants not equipped with NSCR. An estimated 20 percent of HNO₃ plants in the U.S. are equipped with NSCR (Choe, et al., 1993). Therefore, the emission factor is equal to $(9.5 \times 0.80) + (2 \times 0.20) = 8 \text{ kg N}_2\text{O per metric ton HNO}_3$.³

N₂O emissions (Nitric Acid) = [production of Nitric acid] x [(2 kg/ metric ton HNO₃ x 20% of plants) x (9.5 kg/metric ton HNO₃ x 80% of plants)]

1.3 Historical Baseline Emissions

Exhibit 1 shows the historical N₂O emissions associated with adipic and nitric acid production. In 1998, emissions dropped due to the previously discussed abatement measures implemented by the adipic industry.

Exhibit 1. Historical N₂O Emissions from Industrial Processes (MMTCO₂E)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Adipic Acid	18.3	19.1	17.6	19.1	20.2	20.2	20.9	17.2	7.3	8.8
Nitric Acid	18.0	18.0	18.3	18.7	19.4	19.8	20.5	21.3	21.3	20.2
Total	36.3	37.0	35.9	37.8	39.6	40.0	41.4	38.5	28.6	29.3

Source: EPA, 2001.

1.4 Methodology for Forecasting Adipic and Nitric Acid Emissions

Adipic Acid Forecast through 2020. The primary end-users of adipic acid are: Nylon 6/6 manufacturing, accounting for 90 percent of adipic acid use (fibers, 72 percent; resins, 18 percent); polyurethane resins, accounting for 5 percent of use; plasticizers, accounting for 3 percent of use; and miscellaneous (including unsaturated polyester resins and food applications), accounting for 2 percent of adipic acid use (CMR, 1998). Since the main use for adipic acid is as a component of nylon, adipic acid production trends are closely correlated with nylon consumption. The three principal adipic acid plants, representing 98 percent of U.S. production, are projected to expand production capacity by 14 percent between 1999 to 2003. This increase is chiefly due to rising demand for engineering plastics (CW, 1999; CMR, 1998). Though

³ This emission factor is different from that used in the EPA (2000). It has been changed due to further research conducted for the IPCC Expert Meeting on Industrial Gases, Washington, DC January 1999. All subsequent US GHG Inventories will be updated to reflect this change.

production continues to increase, emissions have been significantly reduced due to the widespread installation of pollution control measures. By 1998, all of the major producing plants had implemented N₂O abatement technology, reducing emissions by approximately 92 percent.

Production increases are based on adipic acid field experts' projections (CMR, 1998; SRI Consulting, 1999; Reimer, 1999a), projected GDP growth, historical growth adipic acid production, and planned production capacity expansions in U.S. plants. The historical growth of adipic acid production between 1988 and 1997 was 2 percent per year (CMR, 1988). Planned capacity expansion for the three major existing production plants is 119 thousand metric tons by 2003. Based on this information, it was assumed that future growth in production for all existing production plants and, hence, emissions from 1999 to 2020, will occur at a rate of 3 percent per year.

The N₂O abatement system destruction factor at all production plants is assumed to be 95 percent for catalytic abatement and 98 percent for thermal abatement. The abatement system utilization factor is assumed to be 95 percent for catalytic abatement and 98 percent for thermal abatement and N₂O recycling/utilization technologies through 2020 (Reimer, 1999a).

Nitric Acid Forecast through 2020. Since the main end-uses for nitric acid are as components of fertilizer, explosives, and adipic acid, nitric acid production trends are closely correlated with the consumption/production trends of these three products. The nitric acid production growth estimates are calculated by taking a composite of the growth estimates for ammonium nitrate, aniline and toluene, and adipic acid, weighted by their respective production share. Ammonium nitrate production comprises 80 percent of nitric acid produced, adipic acid production 9 percent, and aniline and toluene production 11 percent. Ammonium nitrate production did not increase between 1998-1999 and is considered to have stabilized. It is estimated to grow at a rate of 0.3 percent between 2000-2020. The production of adipic acid and aniline and toluene are both estimated to grow at rate of 3% in this same time period (SRI, 1999 and Laurient, 2000). By multiplying the growth estimates of the end-uses by their production share, nitric acid emissions are projected to grow at a rate of 0.8 percent annually.

Nitrous oxide emissions from nitric acid production will be influenced by the degree and type of NO_x emission control efforts that are applied in both new and existing nitric acid plants. The forecast assumes that no additional plants will be equipped with non-selective catalytic reduction (NSCR) or N₂O-specific control technologies through 2020.

1.5 Baseline Emissions Forecast

Overall, total nitrous oxide emissions from adipic and nitric acid production were substantially lower in 2000 than in 1990 because of the previously discussed abatement measures that have been implemented in the adipic acid industry. Emissions will grow through 2020, however, in the absence of additional activities to reduce them. Exhibit 2 provides a forecast to 2020 for N₂O emissions from adipic and nitric acid production in the U.S.

**Exhibit 2. Baseline N₂O Emissions Forecast from Industrial Processes
(MMTCO₂E)**

Source	2000	2005	2010	2015	2020
Adipic Acid	9.2	10.5	12.5	14.3	16.9
Nitric Acid	20.5	21.3	22.4	23.1	24.2
Total	29.7	31.9	34.5	37.4	40.7

Totals may not add due to independent rounding.

1.6 Uncertainties

In general, adipic acid emission factors and other default values are more certain than those for nitric acid. The N₂O emission factor for adipic acid production -- 0.3 kg N₂O per kg adipic acid -- is associated with an uncertainty of approximately ± 10 percent (Reimer, 1999a). This uncertainty represents variability in N₂O generation due to differences in the composition of the cyclohexanone and cyclohexanol feedstock (ketone and alcohol) that are used by different manufacturers. Higher ketone content results in increased N₂O generation, whereas higher alcohol content results in less N₂O generation (Reimer, 1999b). An individual plant should be able to determine the production of N₂O (based on HNO₃ consumption) within one percent. The N₂O abatement technology efficiency factor for adipic acid production is associated with an uncertainty of approximately ± 5 percent (Reimer, 1999a).

The default values for nitric acid production are much less certain for two reasons. First, N₂O may be generated in the gauze reactor section of nitric acid production in an unintended byproduct reaction (Cook, 1999). Second, the exhaust gas may or may not be treated to control NO_x, and it is uncertain the extent to which NO_x abatement systems may reduce the N₂O concentration of the treated gas. In addition, the nitric acid industry is not well characterized. A significant degree of uncertainty exists in nitric acid production figures because nitric acid plants are often part of larger production facilities, such as fertilizer or explosive manufacturing. As a result, only a small volume of nitric acid is sold on the open market, making production figures difficult to track. Emissions factors are also difficult to determine because of the large number of plants using many different technologies. Based on expert judgement, it is estimated that the N₂O destruction factor for NSCR nitric acid facilities is associated with an uncertainty of approximately ± 10 percent (Reimer, 1999a).

2. Costs of N₂O Emission Reductions

2.1 Options for Reducing N₂O Emissions

Adipic Acid. Adipic acid producers may employ catalytic destruction, thermal destruction, or various N₂O recycling/utilization technologies to control N₂O emissions. Exhibit 3 describes the abatement options. Currently, the three largest adipic acid producing plants in the U.S. voluntarily control N₂O emissions. Sixty three percent of production employs catalytic

destruction, 34 percent uses thermal destruction, and 3 percent of production has no N₂O abatement measures.

Exhibit 3. Nitrous Oxide Abatement Technologies for Adipic Acid Production

Abatement Technology	N ₂ O Destruction Factor	Extent of Implementation in the U.S.	Description
Catalytic Destruction	90 – 95%	Two plants, comprising of approximately 63% of U.S. production capacity.	N ₂ O destruction is achieved using a N ₂ O decomposing catalyst, metal-zeolite catalysts (i.e., noble metals, precious metals). Using a catalyst allows operation at a much lower temperature (Reimer, 1999a).
Thermal Destruction	98 – 99+%	One plant, comprising approximately 34% of U.S. production capacity.	One example of thermal N ₂ O destruction is the destruction of off-gases in boilers using reducing flame burners with premixed methane (or natural gas) (Reimer, 1999a).
Recycling/Utilization Technologies	90 – 98%	In 2000, a 20,000 metric ton expansion unit at one of the existing U.S. plants will implement an N ₂ O recycling/utilization technology.	This technology uses N ₂ O off-gas as an oxidant to produce phenol from benzene. The phenol produced will be used in the nylon process, with the remaining capacity sold on the open market. Once the technology has been demonstrated successfully, there are plans for expanded use. It is estimated to result in a 20% cost reduction in the production of adipic acid (CW, 1998). Solutia has since announced delayed implementation of this technology.
Recycle to Nitric Acid	98 – 99+%	None currently.	A French company has licensed and implemented a technology patented by DuPont that recycles N ₂ O to produce nitric acid by burning the gas at high temperatures in the presence of steam (CW, 1998). The benefits of this process are two fold: it captures the N ₂ O from adipic acid production and avoids the N ₂ O generated by conventional nitric acid production.

Nitric Acid. Currently, the nitric acid industry controls for NO_x, using both non-selective catalytic reduction (NSCR) and selective catalytic reduction (SCR) technologies. NSCR is very

effective at controlling N₂O while SCR can actually increase N₂O emissions. Exhibit 4 provides a description of the abatement options.

NSCR units were widely installed in nitric acid plants built between 1971 and 1977. Today, however NSCR units are generally not preferred because of high-energy costs and associated high gas temperatures. NSCR uses a fuel and a catalyst to consume free oxygen in the tail gas and convert NO_x to elemental nitrogen (Chartier, 1999). The gas from the NO_x abatement is passed through a gas expander for energy recovery. NSCR units produce stack gases in the 1000°F to 1100°F range that require more exotic materials for constructing the expander and have higher maintenance costs. NSCR can reduce N₂O emissions by 80 to 90 percent. It is estimated that approximately 20 percent of nitric acid plants in the U.S. currently use NSCR (Choe, et al., 1993).

The remaining 80 percent of nitric acid plants use SCR or extended absorption units, neither of which is known to reduce N₂O emissions. Research is underway into materials for catalysts that are applicable for N₂O control in nitric acid plants that do not employ NSCR. Information on the status of the commercial development of these catalysts is not currently available, however.

Exhibit 4. N₂O and NO_x Destruction Factors for NO_x Abatement Technologies

Abatement Technology	N₂O Destruction Factor^a	NO_x Destruction Factor^b	Extent of Implementation in the U.S.	Description
Non-Selective Catalytic Reduction	80-90%	94.7 to 99.1%	Widely installed in plants in the U.S. & Canada built between 1971-1977 (currently Approximately 20% in the U.S.).	Uses a fuel and a catalyst to consume free oxygen in the tail gas and to convert NO _x to elemental nitrogen. The gas from the NO _x abatement is passed through a gas expander for energy recovery.
Selective Catalytic Reduction	0%	86%	Approximately 80% of plants in the U.S. use either SCR or extended absorption.	Uses a catalyst and ammonia in the presence of oxygen to reduce NO _x to elemental nitrogen.
Extended Absorption	0%	93.5-97%	Approximately 80% of plants in the U.S. use either SCR or extended absorption.	Reduces NO _x emissions by increasing absorption efficiency and is achieved by extending the height of an existing tower or by adding a new tower.

a. IPCC, 2000

b. EPA, 1991

2.2 Mitigation Cost Analysis Methodology

Adipic Acid. The principal elements in the cost of thermal destruction of N_2O are capital cost, direct operating costs, which includes costs for operation and maintenance, and natural gas fuel costs. Natural gas fuel costs account for approximately 75 percent of annual costs. The capital and direct operating costs are based on an EPA (1991) analysis of alternative NO_x control measures. The 1991 capital cost and direct operating costs were updated using Vataavuk Air Pollution Control Cost Indices (Vataavuk 1995, Vataavuk 1998). All costs are presented in 1996 constant dollars, and adjusted to 1996 dollars using the GDP deflator from the Budget of the United States Government, Fiscal Year 2001, Historical Tables (USG, 2001). The 1991 natural gas price used is an average annual price (weighted by adipic acid capacity) for industrial consumers in the states of Texas (approximately 65 percent of U.S. adipic acid capacity) and Florida (approximately 35 percent of U.S. adipic acid capacity). The 1998 to 2020 natural gas price forecasts were obtained from the EIA Annual Energy Outlook 2001 (EIA, 2001) and converted into 1996 dollars using the GDP deflator referenced above. Abatement equipment life is assumed to be 20 years and the depreciation period for capital equipment is set at 10 years. The calculations use a discount rate of 8 percent and a tax rate of 40 percent, for consistency with related non- CO_2 greenhouse gas analyses. A summary of the capital, operation and maintenance costs, and the natural gas prices used is the thermal catalytic reduction analysis is shown in Exhibit A.1 in Attachment A.

It should be noted that the estimated annual costs for thermal reduction at adipic acid plants do not include revenue for the recovered heat. No data are available to quantify the heat recovery benefit, although total annual costs and N_2O reduction costs would be reduced.

The cost estimate for catalytic destruction of N_2O is provided by industry sources (Reimer, et. al., 1999). The estimate uses an initial investment range of \$7.3 to \$12 million for three manufacturing plants that utilize catalytic reduction. The estimate uses an 8 percent discount rate.

Nitric Acid. The principal elements involved in the cost estimates for NSCR control of N_2O are capital cost and direct operating costs, which include operating labor, maintenance labor, maintenance materials (including catalyst replacement), and natural gas as fuel. The capital and direct operating costs are based on an EPA (1991) analysis of alternative NO_x control measures. Costs represent an average of three nitric acid plants of different sizes. The 1991 capital costs and direct operating costs were converted to 1996 dollars as described above for adipic acid. The 1991 natural gas price represents the national average annual price for industrial consumers (EIA, 1998). The 1998 to 2020 natural gas price forecast was taken from EIA's Annual Energy Outlook 2001 (EIA, 2001) and converted into 1996 dollars using the GDP deflator referenced above. Natural gas accounts for approximately 75 percent of annual costs. The abatement equipment life, depreciation period for capital, tax rate and discount rate are the same as for adipic acid.

The estimated annual costs for NSCR do not include a return on investment from the reduction of NO_x , which is the primary function of the equipment. NSCR is more effective at abating NO_x

than SCR or extended absorption. Measured NO_x control efficiencies for NSCR range from 94.7 to 99.1 percent compared to 86 percent for SCR (EPA, 1991).

The principal elements of the cost estimates for SCR systems are capital costs and direct operating costs. The latter include costs for anhydrous ammonia, maintenance and supplies, and catalyst replacement. The direct operating costs are based on the EPA (1991) study based on three nitric acid plants. The capital costs are based on 1998 installation costs at three plants of comparable size to the ones analyzed by the EPA study (ICF Kaiser Engineers, 1999). The abatement equipment life, depreciation period for capital, tax rate and discount rate are the same as for adipic acid. The incremental costs of using NSCR for N₂O abatement are based on the difference between the annual cost of NSCR and SCR. A summary of the capital, operation and maintenance costs, and the natural gas prices used in the NSCR and SCR cost abatement analysis is shown in Exhibit A.2 in Attachment A.

2.3 Estimated Costs of N₂O Emission Reductions

Adipic Acid. The emissions reductions from adipic acid production are based on the application of thermal reduction units at the one remaining facility that does not now control for N₂O emissions. Thermal destruction of N₂O from adipic acid production is estimated to reduce emissions by 96 percent costing approximately \$0.21 per TCO₂E of reduction in 2010 (Reimer, et. al., 1999). N₂O reductions due to catalytic reduction technology could not be analyzed due to the lack of plant level data. The estimated costs of reducing N₂O emissions are therefore a conservative estimate. Exhibit 5 provides the estimated costs associated with reducing N₂O emissions at adipic acid production facilities using thermal destruction technology.

No cost data are available for recycling technologies. However, recycling technologies in other countries have reported significant savings (CW, 1998). N₂O recycling is planned for at least one plant in the U.S. (see Exhibit 3 on reduction technologies).

Nitric Acid. Exhibit 5 also shows the cost of two approaches for reducing emissions from nitric acid plants. Approximately 80 percent of current plants do not employ NSCR. To control N₂O emissions at these plants requires either prompt replacement of the current system for NO_x control with NSCR or waiting until the current equipment is retired before replacing it with NSCR. The former approach involves a full cost calculation for NSCR; the latter involves only an incremental cost calculation of the difference between the annual cost of NSCR and SCR. In 2010, approximately 85 percent of N₂O emissions can be reduced using NSCR at nitric acid plants. The estimated cost of replacing SCR with NSCR before the natural turnover in capital is approximately \$2.59 per TCO₂E in 2010. The estimated cost of installing NSCR units when capital equipment is replaced is \$1.22 per TCO₂E in 2010.

The cost of using extended absorption to control N₂O emissions is not compared to NSCR in this study. This process receives a significant credit for recovered acid; however, not all plants are able to utilize the recycled acid.

Exhibit 5. Cost of Reducing N₂O Emissions from Industrial Processes

Abatement Technology	Year	Cost (1996\$/TCO₂)	Emissions Available for Reduction (MMTCO₂E/Year)	N₂O Destruction Factor	Emission Reduction (MMTCO₂E/Year)
Adipic Acid:					
Thermal Destruction Technology					
	2005	0.21	2.14	96	2.05
	2010	0.21	2.14	96	2.05
	2015	0.21	2.14	96	2.05
	2020	0.22	2.14	96	2.05
Nitric Acid:					
NSCR Technology: <i>Replacement Cost*</i>					
	2005	2.58	20.23	85	17.19
	2010	2.59	21.09	85	17.93
	2015	2.59	21.99	85	18.69
	2020	2.68	22.93	85	19.49
Nitric Acid:					
NSCR Technology: <i>Incremental Cost**</i>					
	2005	1.22	20.23	85	17.19
	2010	1.22	21.09	85	17.93
	2015	1.23	21.99	85	18.69
	2020	1.32	22.93	85	19.49

*Incremental Cost refers to the prompt installation of this technology

**Replacement Cost refers to installation of this technology when the current technology is retired.

2.4 Uncertainties

The cost estimates for N₂O control at adipic and nitric acid plants are based on 1991 estimates for NO_x control technologies. The accuracy of the estimates could be improved by obtaining more recent cost data and by developing cost data specific to N₂O controls instead of the compatible NO_x control technologies.

The estimated annual costs for thermal reduction at adipic acid plants do not include cost-savings from the recovered heat. Thermal reduction units generate heat through combustion, and it is normally recovered as steam for use elsewhere at the facility (EPA, 1991). No data are available to determine the amount of this cost-savings, although total annual costs and N₂O reduction costs would be reduced.

Given the research and development that has been conducted on catalysts for N₂O control in non-NSCR applications at nitric acid plants, future analyses should assess the potential of new technologies. For example, if companies could earn revenue for reducing N₂O emissions, the removal effectiveness of currently available N₂O control technologies could improve.

Furthermore, since many nitric acid production facilities are between 20 and 30 years old (CMR, 1995), there may be many opportunities to install or update emissions control technologies. If it is necessary to completely replace control technologies at a specific plant then only incremental costs between technologies should be considered. Further analysis could be conducted to better characterize U.S. nitric acid plants in order to understand what opportunities exist and at what costs.

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Attachment A: Capital and Operation and Maintenance Costs for Mitigation Options

A.1 Costs of Implementing Thermal Reduction Applied to Adipic Acid Manufacture

Costs of implementing thermal reduction to adipic acid manufacturing were calculated by adjusting 1991 cost data obtained from the EPA (1991)⁴ to 1996 dollars using a deflation factor from NASA,⁵ to be consistent with other EPA analyses.

Exhibit A.1: Adipic Acid - Capital and Operation and Maintenance Cost Estimates for Thermal Reduction by Plant Capacity (1991\$)

Plant Capacity (Mg/year)	Capital Cost (\$ in millions)	O&M (\$ in millions)
23,000	0.87	0.27
272,400	7.0	1.8
317,800	8.0	2.1

Estimates represent 1991 dollars

A.2. Costs of Implementing Nonselective and Selective Catalytic Reduction to Nitric Acid Manufacture

Costs of implementing non-selective and selective catalytic reduction to nitric acid manufacturing were calculated by adjusting 1991 cost data from the EPA (1991) to 1996 dollars in the same manner as for adipic acid. For selective catalytic reduction, costs are lower since the technology controls for NO_x as well as N₂O emissions. The costs for selective catalytic reduction were calculated in order to obtain the incremental cost of using NSCR units for N₂O abatement. The incremental cost of using NSCR units was calculated by taking the difference between the cost of using an NSCR unit and the cost of using a SCR unit.

Exhibit A.2: Nitric Acid – Capital and Operation and Maintenance Cost Estimates for Nonselective Catalytic Reduction and Selective Catalytic Reduction by Plant Capacity (1991\$)

Plant Capacity (Mg/year)	Non-selective Catalytic Reduction		Selective Catalytic Reduction	
	Capital Cost (\$ in millions)	O&M (\$ in millions)	Capital Cost (\$ in millions)	O&M (\$ in millions)
66,065	1.1	.28	.50	.13
165,710	1.9	.64	.73	.37
331,055	2.8	1.2	1.0	.62

⁴ EPA, 1991. Alternative Control Techniques Document – Nitric and Adipic Acid Manufacturing Plants.

⁵ NASA, 2001, <http://www.jsc.nasa.gov/bu2/inflateGDP.html>

A.3. Natural Gas Prices

Exhibit A.3 displays the natural gas price forecast used in estimating the operation and maintenance costs for thermal destruction and Non-Selective Catalytic Reduction.

Exhibit A.3: Natural Gas Prices Used in Estimating Costs for Thermal Destruction and Nonselective Catalytic Reduction

Natural Gas Price	1998	2000	2005	2010	2015	2020
Delivered Gas Price: National Average (99\$/1000ft³)	4.13	5.15	4.35	4.38	4.39	4.62
Delivered Gas Price: National Average (96\$/1000ft³)	3.96	4.94	4.17	4.20	4.21	4.43

Source: EIA Annual Energy Outlook 2001